# Understanding Magnetic Flux Leakage (MFL) Signals from Mechanical Damage in Pipelines

## 3rd QUARTERLY PUBLIC REPORT

**Period: September through December 2005**

## Background

The objective of this project is to understand the origin of Magnetic Flux Leakage (MFL) signals from dents, the ultimate goal being to accurately characterize dents from MFL field inspection data. MFL dent signals arise from both the dent geometry as well as the residual stresses surrounding the dent. In this project, experimental and finite element modelling techniques are used to separate and understand the individual stress and geometry components of the MFL signals.

Earlier work (pre-2005) by the Queen's University Applied Magnetics Group involved examination of MFL signals from circular dents. The present US DOT PHMSA contract extends this study to include oval or "elongated" dents; specifically dents having a 2:1 length to width aspect ratio.

In the first quarter of the contract, an oval denting tool was designed and constructed for use in the experimental part of the study. On the modeling side, stress Finite Element Analysis (FEA) modeling was conducted for simulated 2:1 aspect ratio elongated dents. In addition, magnetic FEA modeling was begun which utilized the stress FEA modeling results.

In the second quarter of this contract, work continued on both the experimental and FEA modeling efforts. Specifically, the second quarter focused primarily on modeling and experimental studies of MFL signals from dents elongated in the **axial** direction of the pipe. All subtasks for the second quarter were completed satisfactorily and on schedule.

## Summary of Progress this Quarter

In this, the third quarter of the contract, the work has again been of both FEA modeling and experimental nature, however, in this quarter the focus has been two-fold:

- modeling and experimental studies of MFL signals from dents elongated in the **circumferential** pipe direction (subtasks 1.5 and 1.6), and
- modeling and experimental studies of MFL signals from circular dents containing a central corrosion pit (subtasks 2.2 and 2.3).

Subtask 1.4 (experimental MFL work on axially-oriented dents), which began in the second quarter, was also completed. Also in this quarter was the annual PRCI meeting which included presentation of interim results for this project to technical representatives of the major oil and gas companies and pipeline inspection companies belonging to PRCI. A number of meetings were held with representatives of Gaz de France, who will collaborate with Queen's in next year's work. Finally, Dr. Clapham was invited to visit BMT Fleet Technologies to discuss various aspects of the work. BMT is an international consulting company that develops mechanical models for dent behavior to develop failure criteria.

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# Results

**Generalized experimental procedure**

Samples: Steel plate samples of dimensions 260 mm x150 mm x 3 mm thick were dented using a hydraulic press fitted with the 2:1 aspect ratio oval denting tool and die that was designed and constructed in Task 1.1. Dent depths ranged between 3 mm and 7 mm. The resulting dent size (length and width) in each sample varied depending on the dent depth, but was approximately 45 mm x 25 mm. MFL scans were obtained for each sample using the methods described below. Under these conditions the MFL signal is generated both by the dent geometry as well as the residual stresses around the dent. After the initial MFL scans were complete, the dented samples were heat treated at 500$^{o}$C for 2 hours to relieve most of the residual stresses associated with the denting process. The MFL scanning was then repeated, with this post-annealing MFL result primarily associated with the dent geometry.

MFL scanning equipment: A schematic diagram of Queen's laboratory MFL detection system is shown in Figure 1. This shows the side view of an MFL circuit sitting on the dented sample (in cross section). The MFL circuit includes high strength Nd-Fe-B permanent magnets and steel pole pieces to couple the flux into the sample. The MFL magnet is configured to produce a sample flux density of 1.5T.

A Hall probe detector is attached to the arm of an XY plotter (not shown), and during an MFL measurement ,it scans over a 40 mm x 40 mm area above the dented region at 1 mm intervals. The diagram in Figure 1 shows the Hall probe travelling over the "bottomside" of a dented sample, and illustrates that the probe itself does not follow the local surface contour but rather remains parallel to the undented surface as it passes over the dent. This is consistent with MFL inspection scans in the field.

The Hall probe can be oriented to measure either the axial, radial or circumferential components of the leakage flux signal, and is connected though an amplifier to a PC-based data acquisition system. The results of the 40 mm x 40 mm Hall probe scans are typically displayed as contour plots.

The bottomside scan configuration is similar to the type of MFL measurement made in a typical pipeline inspection scenario, since the inspection tool is inside the pipe. In the present study we have also conducted 'topside' MFL scans. These are done using the configuration shown in Figure 1 except that the sample is 'flipped' to scan over the other side. The topside scan would correspond to a scan of the outer pipe surface, something that is rarely done in practice. Despite this, the topside measurement is useful for comparison with bottomside results and aids in interpreting contour plots, therefore, both topside and bottomside measurement on all dented samples are obtained.

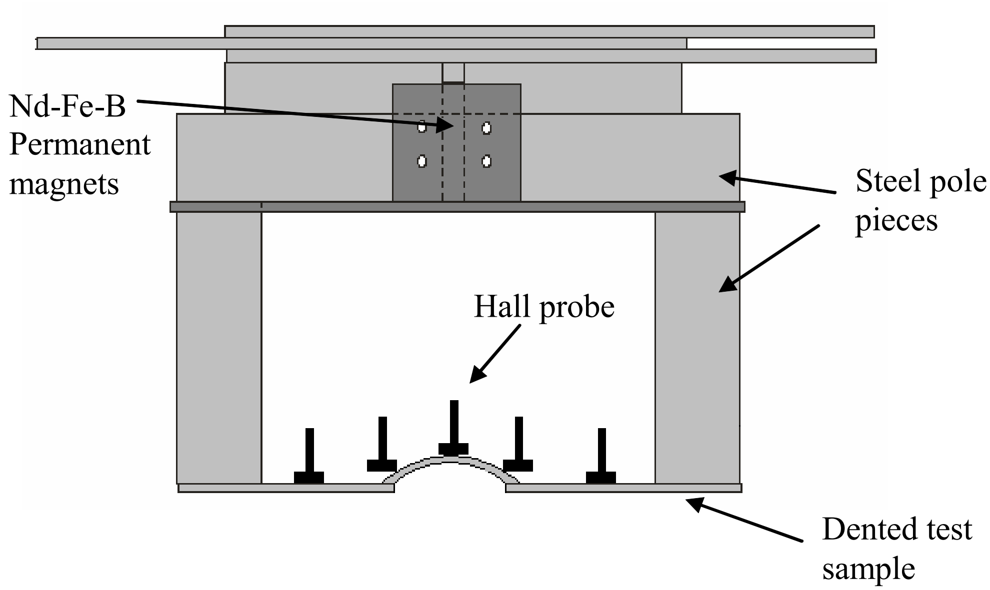


*Figure 1: Side view of a typical laboratory MFL detection system. Only a single Hall probe is used and the diagram illustrates how it steps over the dent surface during a typical scan.*

## Experimental observations of MFL patterns around axially-oriented oval dents

Example results of MFL scans of 2:1 axially-oriented dents before annealing were shown in the previous quarterly report. In the third quarter, the work was completed for topside and bottomside measurements, for all 3 components of the MFL field, and before and after annealing. As an example of this work, Figure 2 shows typical MFL radial component bottomside signals, before and after annealing, for the 3 mm and 7 mm dent depths. Earlier work on the circular dents indicated that the central features of the contour plot are geometry-related, while the 'shoulder' peaks tend to be stress-related. Similar stress-related 'shoulder' features have also been observed the elongated dents of the present study, both in experimental and modelling results.

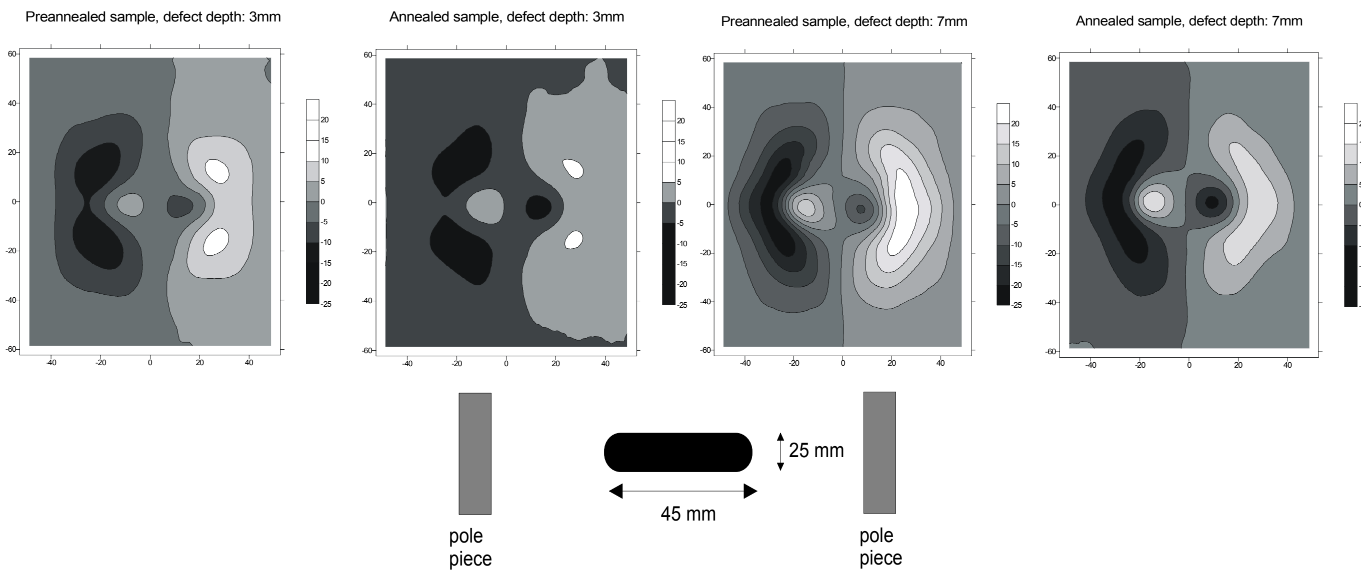


*Figure 2 MFL radial component contour plots for the bottomside of the 2:1 dent, for dent depths of 3 mm (top) and 7 mm(bottom). Results on the left are before annealing, on the right are after annealing. The gray scale label on the side is in units of $B_{radial}$ x $10^{-4}$T. The schematic diagram at the bottom indicates the orientation of the dent relative to the magnet pole pieces and the contour plots.*

## Modelling MFL patterns around circumferentially-oriented elongated dents

Quarterly report 1 provided details of the stress FEA modelling used to obtain the residual stress distribution around the dent. This information was used to assign specific stress-related permeability functions to particular regions around the dent in the magnetic FEA model.

Figure 3 shows the magnetic model constructed for the circumferentially-oriented elongated dent (only a quarter model is necessary because of geometric and loading symmetries). The modelled dent is 7 mm deep. The segments in and around the dent indicate the regions where different permeabilities can be assigned. There are a total of 112 separate segments in this model. Note that the finite element mesh is much smaller than the size of these segments.

Examination of the stress FEA model (explained in Quarterly report 1) was used to determine the levels and directions of residual stress in the dent region. Magnetic permeability functions were assigned to the dent segments in Figure 3 according to the level of residual stress predicted by the stress FEA model. In Figure 3, for example, green segments have low (essentially zero) residual stresses; blue segments compressive stress, and purple tensile stress. Note also that the permeability function is a vector, therefore the stress direction is critical to the analysis and the model.

The advantage of the magnetic FEA model is that it is possible to 'isolate' either stress or geometry MFL signals. The geometry-only signal is created by assigning all of the segments in Figure 3 with the same isotropic permeability function that is present in the background plate. The geometry-only MFL (radial component) signal is shown in Figure 4.

The stress-only MFL (radial) signal is generated in two steps – 1) the geometry+stress result is obtained using the geometric model shown in Figure 3 which contains residual stress-altered permeability regions, and then 2) the geometry-only result (figure 4) is subtracted from this result. The stress-only MFL (radial) result is shown in Figure 5. It is worthwhile noting further that within the stress model, each individual stress region can be turned "off" or "on" separately. This enables us to determine exactly which stresses are responsible for each peak.

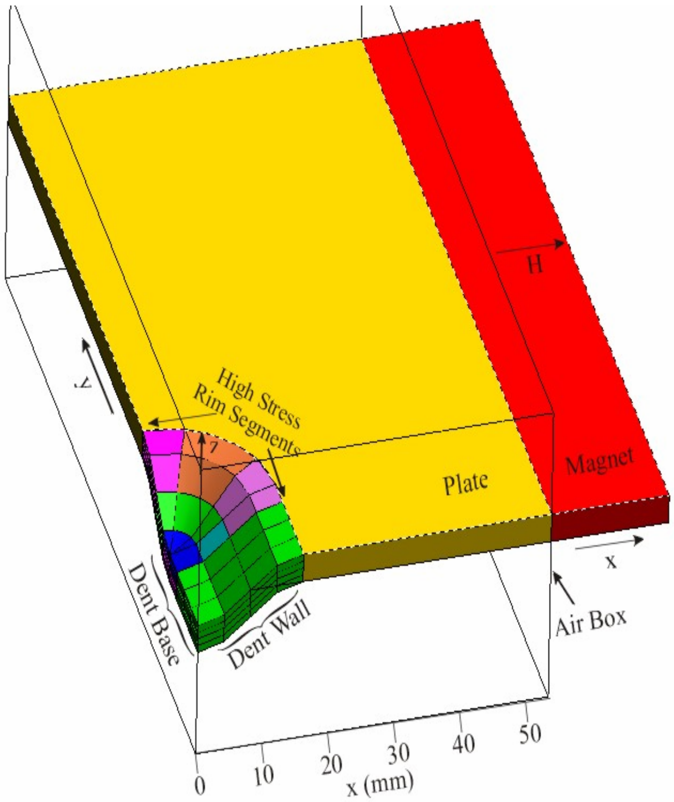


*Figure 3: The magnetic FEA model (quarter-model) for the circumferentially elongated dent. The magnet region is shown in red. Only a quarter model is necessary due to symmetry. The dent region is divided into 112 segments. Each of these segments can be assigned a different magnetic permeability according to the residual stress predicted in that segment.*

Figure 6 shows the combined stress+geometry MFL radial component result containing all of the significant residual stress regions indicated by the stress FEA model. MFL axial and circumferential model results were also obtained but are not shown here.

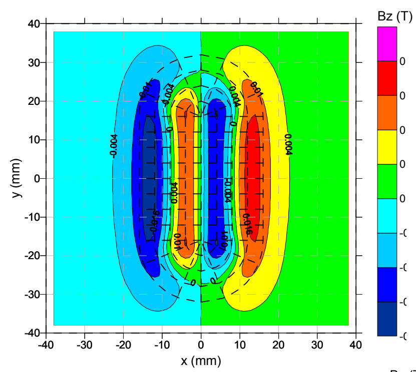


*Figure 4: MFL radial component (z direction) geometry-only contour plot for the 2:1 circumferentially elongated dent model shown in Figure 3. The dotted line on the plot indicates the dent perimeter.*

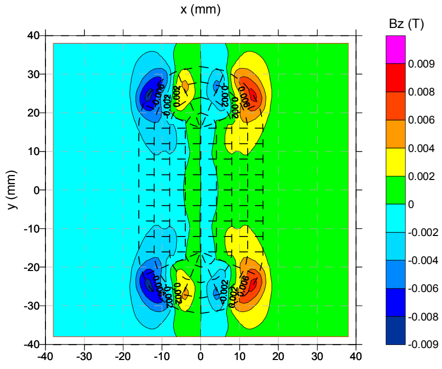


*Figure 5: MFL radial component (z direction) stress-only contour plot for the 2:1 circumferentially elongated dent model shown in Figure 3. The dotted lines on the figure indicate the dent perimeter and the lines on top of the dent are the individual segments seen in plan view. Note that the scale is different than for the geometry-only case in figure 4 – such that the maximum MFL value in Figure 5 is approximately half that of Figure 4.*

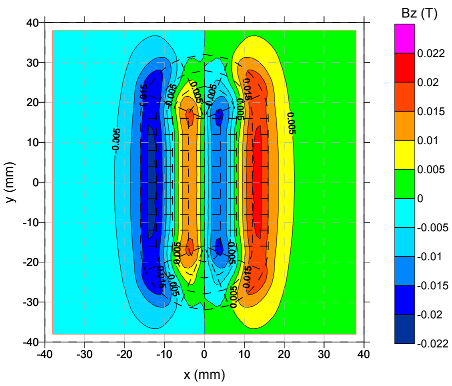


*Figure 6: Combined stress+geometry MFL contour plot (radial component) for the 2:1 circumferentially elongated dent, obtained from the magnetic FEA model*

**Experimental studies of MFL patterns around circumferentially oriented dents**

Experimental procedures for studying MFL signals from circumferentially oriented dents were as described at the beginning of this section. Work included topside and bottomside MFL measurements, for all 3 components of the MFL field, before and after annealing. Figure 7 shows a typical result; in this case MFL radial component bottomside signals, before and after annealing, for the 3 mm and 7 mm dent depths.

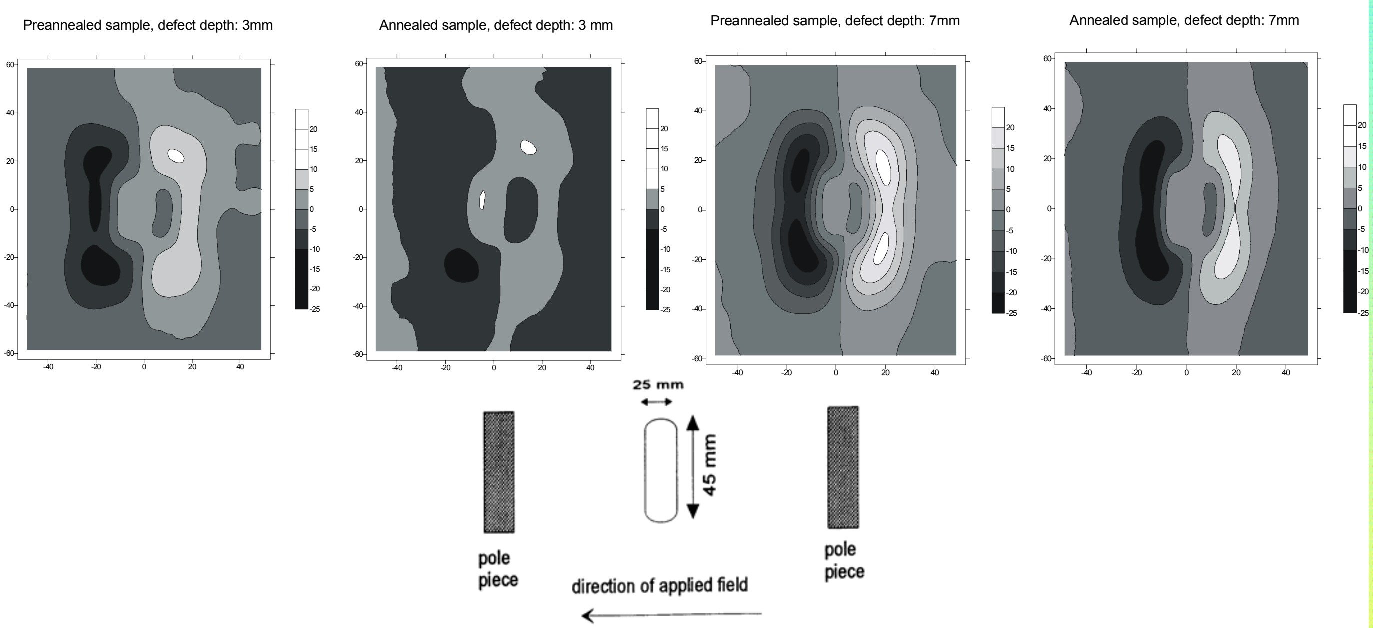


*Figure 7: Experimental MFL contour plot (radial component) for a bottomside scan, 2:1 circumferentially oriented dents of 3 and 7 mm depth. Left hand side shows the result before annealing, the right hand side result after annealing.*

**Modelling MFL patterns from circular dents containing corrosion pits**

Dents containing included corrosion pits are a particular concern because they represent an enhanced (and coupled) threat condition. In this study, 40 mm diameter circular dents were considered with 8 mm circular corrosion pits included at the base of the dent. Figure 8 shows the FEA model for the circular dent + pit. Figure 9 shows a typical modelled MFL (radial component) bottomside signal resulting from this circular dent+pit.

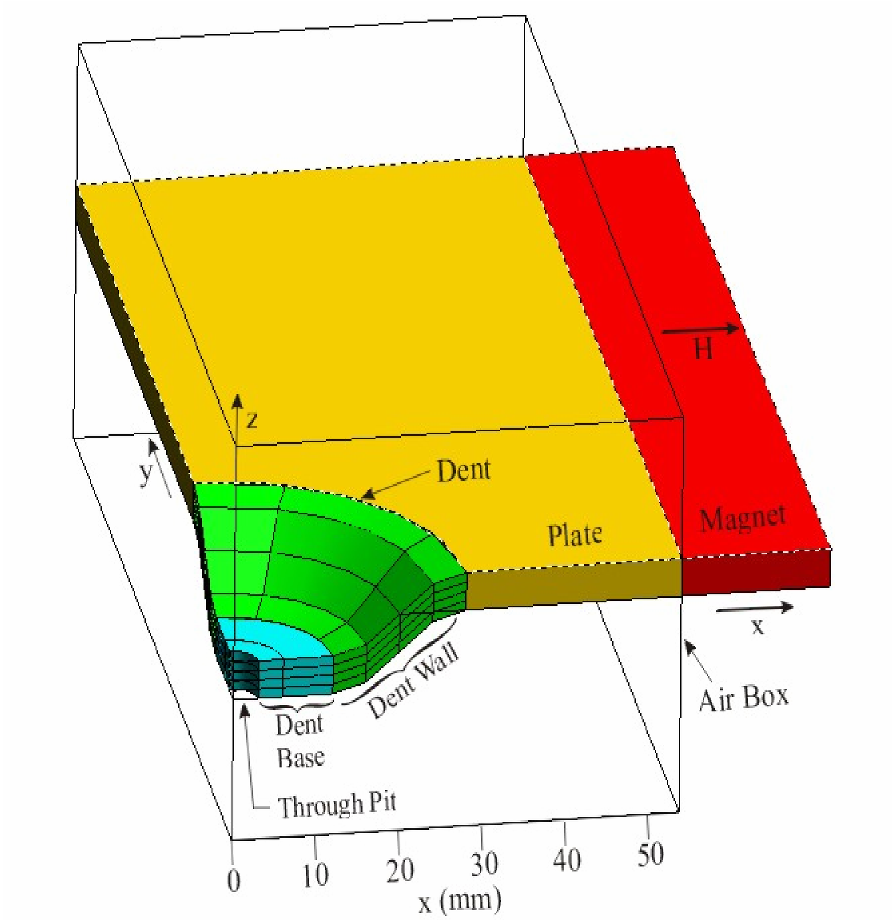


*Figure 8: FEA quarter model of a circular dent containing an included corrosion pit at the base (bottom left-hand corner of the model).*

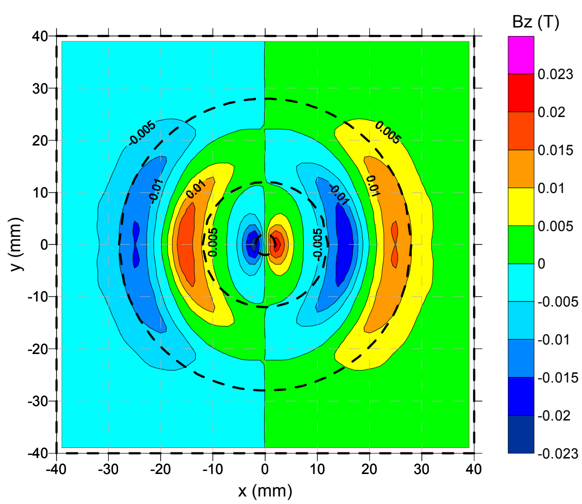


*Figure 9: Modelled bottomside MFL contour plot (radial component) for a circular dent +pit. The dent signal is for the geometry signal only.*

## Experimental studies of MFL signals from circular dents containing corrosion pits

The dents in this study were produced in a similar fashion to the 2:1 elongated dents, except circular denting tools were used rather than an elongated one. After denting, small (~6 mm diameter) circular corrosion pits were introduced at the base of the dents. An electrochemical milling (ECM) device was used to create the pit to avoid introducing stress and to closely mimic the corrosion process. The pit was through-wall. Figure 10 shows the experimental results for dents of two diameters (3 and 5 mm) containing through-wall pits, as well as a typical result from a pit with no dent for comparison. As in the modelled result of Figure 9, the smaller pit signal can be seen at the dent centre, surrounded by the dent signal.

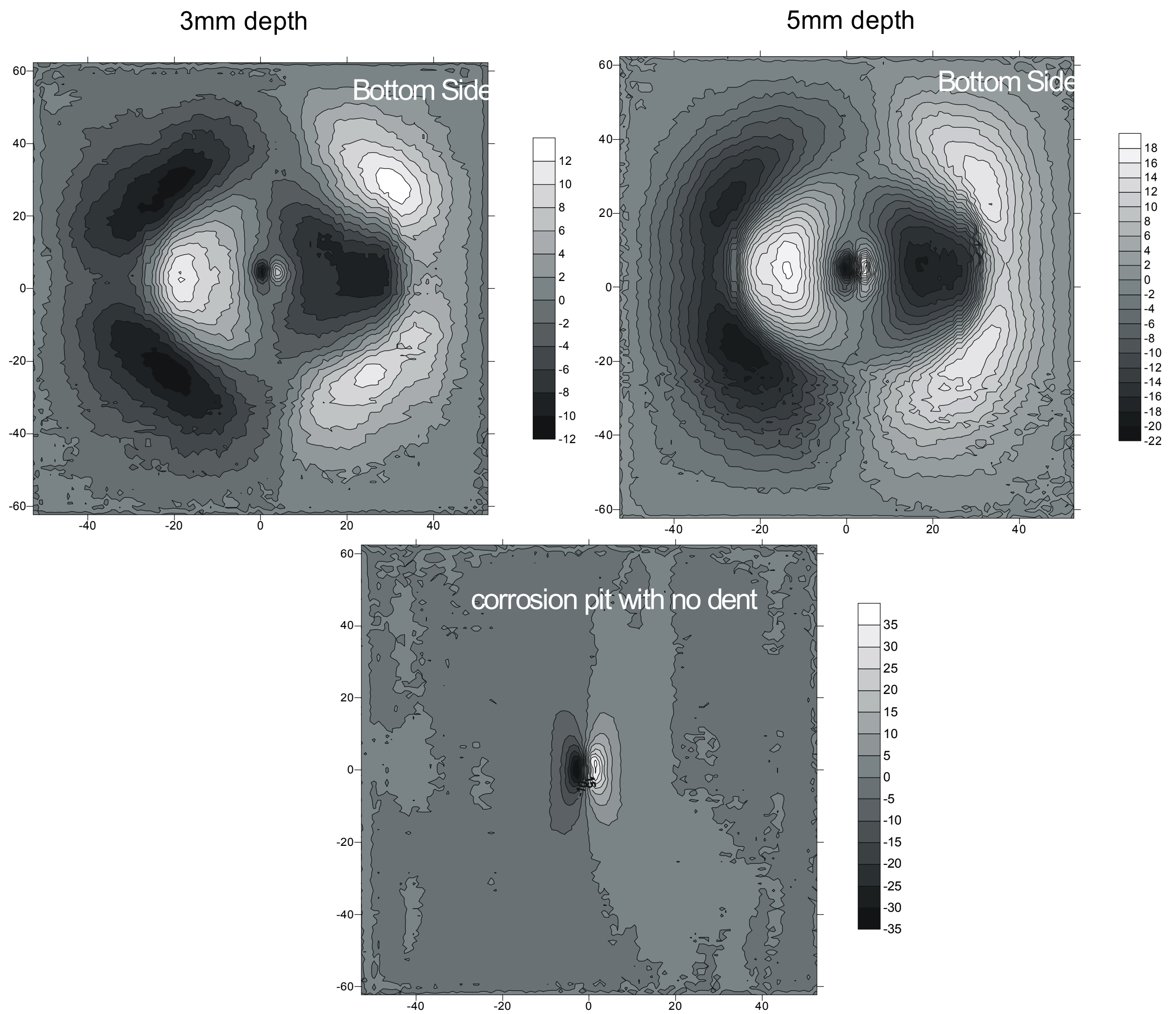


*Figure 10: Experimental bottomside MFL contour plot (radial component) for a samples containing corrosion pits – the top two plots are for 3 mm deep (left) and 5mm deep (right) dents containing pits, while the bottom plot is the result for a corrosion pit with no dent.*

## Future Activities

Planned activity over the next 90 days will include work on all subtasks related to the fourth milestone identified in the agreement. These include:

- Preliminary study of backhoe dent results for use in follow-on magnetic modeling studies.
- Final report including database and conference presentation prepared.

Additionally, the project team will be participating in the Peer Reviews of the work conducted to date on this project.

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